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The effects of horizontal advection on the Urban Heat Island in Birmingham and the West Midlands, UK during a heatwave

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Abstract

Birmingham is the second most populous city in the UK and observations indicate it has a pronounced urban heat island (UHI), i.e. higher ambient temperatures in the city centre compared to surrounding suburban and rural areas, particularly at night. The effects of UHIs are often amplified during anticyclonic summer weather conditions, which can cause or exacerbate heatwaves. Enhanced temperatures in highly populated regions can mean that significant numbers of people are at risk from heat related illness during hot weather. Climate change projections often do not include the effects of the UHI, which can mean that assessments of heat related health effects using climate change projections underestimate the actual magnitude of future health impacts.

We present numerical simulations of the UHI in Birmingham and the West Midlands Metropolitan region during the heatwave of August 2003 using a high resolution, regional meteorological model (WRF) with an urban canopy scheme. We evaluated the model using local air temperature observations, and found good model performance in capturing the temporal and spatial signature of the UHI. We performed a sensitivity test, replacing urban land categories with rural ones, and found the difference in temperature between the 2 model runs throughout the heatwave period (2nd to 11th August 2003) was around 3^{o}C on average, and reached a maximum of 7^{o}C. Finally, we present a novel generic methodology to enable the examination of the extent of horizontal advection of warm air downwind of the conurbation area. We found that during the heatwave, temperatures downwind of Birmingham were up to 2.5^{o}C warmer than those upwind. This methodology has the potential for improvements to or parameterizations for diagnostic models which do not explicitly include dynamics and where local conditions are driven largely by land surface type.

Key words (up to 8)

UHI, WRF, Building Energy Parameterization, climate change, advection.

Short title:

Effects of horizontal advection on the Birmingham Urban Heat Island

1 Introduction

The Urban Heat Island (UHI) is a well-studied phenomenon which describes the fact that urbanised areas regularly experience higher night-time ambient temperatures than rural or suburban surroundings, due to differences in the local surface energy balance. The main factors contributing to the urban temperature increment are the physical properties of urban materials, building geometry, reduced sky-view factor and a lack of vegetation and moisture (Oke, 1982). The UHI intensity is often enhanced during anticyclonic summer weather, when winds are low and skies are clear. Enhanced temperatures in cities and towns where there is a high population density can mean that significant numbers of people are at risk from heat related illness during hot weather. This health risk is likely to be exacerbated in the future, as summer temperatures continue to rise due to climate change (Hajat *et al*., 2014). In addition, projected rates of urban growth and an ageing population in the UK mean that vulnerability to hot weather is likely to increase.

During August 2003, a combination of long lasting anticyclonic conditions, low soil moisture and drought conditions led to a severe heatwave across Europe. The heatwave had many impacts, most notably on health, and was considered to be responsible for up to 70,000 excess deaths across Europe (Robine *et al*., 2008). There were further impacts on the environment, agriculture and ecosystems, particularly in Western Europe (Garcia-Herrera *et al.*, 2010). A number of record breaking temperatures were observed, with temperatures reaching over 45^{o}C in some parts of Europe. In the UK, the warmest conditions occurred at the beginning of August, with the highest temperature for the UK ever recorded (38.5^{o}C) in Kent, south east England. There were over 2,000 deaths attributed to the heatwave in England (Johnson *et al*., 2005).

The UKCP09 climate projections from the UK Climate Impacts Programme (http://ukclimateprojections.metoffice.gov.uk/) indicate that depending on location within the UK, annual mean air temperatures are likely to rise between 2 and 5^{o}C under medium emissions (based on the SRES A1B scenario) by 2080, and summer maximum temperatures will rise more. As well as increases in mean temperature, climate change is also likely to lead to an increase in the frequency of heatwaves (Schär *et al.*, 2004; Stott *et al.*, 2004), which will be particularly noticeable in urban areas, due to the UHI effect. Climate projections such as UKCP09 do not include urban surface schemes due to the difficulty in resolving fine details in climate models, and the fact that urban conglomerations are often smaller than the model grid squares (Jenkins *et al*., 2009). This means that future health impacts due to heat calculated using these climate change projections may be underestimated. In order to fully quantify the heat related health impacts of climate change, it is necessary to model the UHI intensity, and combine it with regional climate change projections.

Birmingham is the second largest city in the UK by population, with just over 1 million inhabitants. It is surrounded by a number of cities and towns and has an extensive road network, indicating that large numbers of people are exposed to enhanced ambient temperatures due to the effects of intense urbanisation (Figure 1). Attempts have been made to measure the intensity of the UHI of Birmingham by a variety of methods. Unwin (1980) investigated the UHI over the period 1965-1974 using 2 observational sites to represent rural and urban areas. Differences in daily minimum temperatures between the urban and rural sites were found to be largest under anticyclonic conditions, and the UHI in Birmingham was most pronounced in the warmer half of the year. The use of only 2 weather stations for this investigation, neither of which can be completely classified as urban or rural, and which are located at different heights, is acknowledged to limit the completeness of the study. Furthermore, Unwin (1980) acknowledges a patchwork of individual microclimates in Birmingham which are not captured by monitoring.

Rather than use maximum and minimum temperatures, which may be recorded at different times of the day, Johnson (1985) used heating and cooling rates to investigate how the urban surface modified the evolution of the UHI in Birmingham, and allowed identification of the point in time at which urban and rural areas behave differently in terms of heating and cooling rates. The use of a transect (27 monitoring sites over 20 km) was an improvement compared to the use of isolated observational sites, although the measurements were taken consecutively, rather than at the same time at each site. The generation and dissipation of the UHI was related to differentials in heating and cooling rates which are influenced by ambient weather and land use. The UHI intensity was found to be largest at night (up to 4.5^{o}C) and in clear, calm atmospheric conditions.

Estimates of the Birmingham UHI intensity have been made using satellite data, for a range of different atmospheric stability classes (Tomlinson *et al.*, 2012). The use of satellite images gives a good representation of spatial variability in surface temperature across Birmingham, although due to data availability, only night-time snapshots on clear nights could be used and the quantity measured is land surface temperature, rather than air temperature. The estimates indicated that during the July 2006 heatwave period, which was estimated to have led to around 170 excess deaths in the West Midlands (ONS, 2006), the night-time UHI intensity was particularly large: up to 7^{o}C (Tomlinson *et al*., 2012).

Although the existing published literature gives an indication of the intensity of the UHI in the West Midlands, much of the work uses a limited number of point measurements, or spatial maps which are limited in time or only available for certain weather types. One way to address these particular shortcomings is by using a regional meteorological model such as WRF (the Weather Research and Forecasting model) to simulate the UHI intensity in cities. Regional meteorological models run at high resolution can be combined with realistic local urban land-use maps to simulate local weather conditions for the region of interest. This is an established method and has been used recently for studies of London, using a 2D urban surface scheme (Bohnenstengel *et al*., 2011). Other cities have also been modelled using WRF over a 2 day heatwave in Madrid (Salamanca *et al.*, 2012) and Athens (Giannaros *et al.*, 2013) as well as in an Alpine Valley and including the city of Trento (Giovannini *et al.*, 2013). A study based in Brussels used dynamical downscaling to investigate how urban and rural areas are likely respond to future climate change using the Town Energy Balance scheme (Hamdi *et al.*, 2013).

Following the previous literature which has successfully used WRF for simulations of large cities, we present the first study to use WRF to simulate the UHI for Birmingham and the West Midlands, UK. We have validated the model against observations to ensure satisfactory model performance. We quantify the intensity of the UHI across the region during a heatwave, and investigate the sensitivity of temperatures to land use type. In addition, we consider the effects of prevailing winds on horizontal advection of warm air downwind of the urban centre by considering differences in surface air temperatures upwind and downwind of the city centre as a function of prevailing wind direction. It is anticipated that the simulated temperatures within and downwind of cities can be used to inform health impact assessment work in future and to identify vulnerable populations.

2 Methods and observational data

2.1 Met Office observation stations in the West Midlands

Data from the Met Office Integrated Data Archive System (MIDAS) land surface weather stations in the West Midlands area were provided by the British Atmospheric Data Centre (http://badc.nerc.ac.uk). There are few temperature monitoring stations in Birmingham and the West Midlands, of which four have suitable data coverage over the August 2003 heatwave period. The weather station based at Edgbaston (EB) is often used to represent the urban centre of Birmingham, although the site is around 3 km south west from the centre of the city, and is more accurately described as 'semi-urban'. This is because historically, weather stations were positioned outside of city centres so as not to be influenced by urban factors. The EB station is positioned near to a recreation ground and reservoir; however, due to its proximity to Birmingham city centre, it is used here to represent an urban site. Coleshill monitoring station (CH) is located around 16 km to the east of Birmingham Centre, on a farm site away from urbanised areas, and so represents a rural site. In the following sections, we use CH as a rural site to compare with an urban site (EB) for the Birmingham area. The two other stations which were used for model evaluation (Section 2.4) were Wolverhampton (WH) and Coventry (CV). Both of these stations can be described as urban, since they are positioned within the city centres. WH is about 20 km to the north west of Birmingham, and the land-use between WH and Birmingham is largely urban or suburban. CV is a city approximately 30 km east south east of Birmingham. Between the 2 cities is a mixture of urban, suburban and rural land types (Figure 1).

2.2 Urban and rural temperature and wind observations during August 2003

Figure 2 shows observed air temperature at screen height (1.5 m) from the 2^{nd} – 10^{th} August 2003 at CH (rural) and EB (urban) sites. CH generally has higher daytime and lower night-time temperatures, and hence a larger diurnal range than EB: a mean range of 14.6^{o}C at CH over the observation period, compared with 11.8^{o}C at EB. The difference in temperatures between the two stations is greater at night, where the maximum difference is 4.7^{o}C (EB warmer) compared with 3.2^{o}C (CH warmer) during the day. The average difference between air temperature measurements at EB and CH over the period is 0.5^{o}C. By comparing hourly mean EB and CH temperatures, we can estimate the maximum UHI intensity during the heatwave period, although a direct comparison in this way does not take into account the systematic difference in temperature between the two sites due to factors other than land use, for example, the climatological temperature lapse rate due to the difference in elevation. If the lapse rate (assumed to be -5 ^{o}C km^{-1}) is corrected for, the UHI intensity would be 0.32 ^{o}C higher since EB's elevation is 160 m and CH's elevation is 96 m. In other words, the UHI intensity calculated from the direct temperature measurements at the two sites underestimates the true UHI intensity.

The UHI is often enhanced during low wind speed conditions, whereas stronger winds can provide stronger mixing between the warmer air in the urban canopy layer and the overlying cooler air, and between the warmer city air and the cooler surrounding air. Figure 3 shows a time-series of wind speed and temperature for all hours during the heatwave. The diurnal variations of UHI intensity and wind speed are strongly anti-correlated, with the highest CH wind speeds during the day time, which can be partially attributed to strong boundary layer mixing, and the highest UHI and lowest wind speeds at night time.

Although there are clear differences in the diurnal cycle of temperatures between EB and CH monitoring stations during the start of August 2003 (Figure 2), and an inverse relationship between wind speed and UHI intensity (Figure 3), the observations recorded at each station are influenced by a range of factors, including atmospheric stability and advection by wind, and it is not possible to gain an insight into these mechanisms based on data from a few stations. This motivates a spatial analysis using modelled temperatures.

2.3 Modelling methodology

Following an initial analysis of observations from weather stations, we simulated weather conditions, including 2 m temperature, across the West Midlands using a high resolution run of the Weather Research and Forecasting model (WRF-ARW) version 3.2 (Skamarock *et al.*, 2008). In addition, we used the multi-layer Building Energy Parameterization (BEP) scheme (Martilli *et al*., 2002) with three separate urban surface categories for the central West Midlands area. To evaluate the model, we used observational data from the Met Office weather stations detailed in Section 2.1. The model was run continuously over the time period chosen for the simulation (1^{st} – 10^{th}August 2003), when anticyclonic conditions over the UK resulted in light winds and largely cloud-free conditions which were favourable for the development of an UHI.

To enable a more thorough understanding of the influence that urban surfaces have on local climate, we compared output from the model which incorporated detailed urban land surface information for the West Midlands with a simulation where urban land surface categories (industrial/commercial, high intensity residential and low intensity residential) were replaced with a rural category (dryland cropland and pasture). This sensitivity test (described in Section 3.1) allowed us to compare temperatures at the same location and time, depending on two different land use types , and hence estimate the urban influence on local temperatures at any given point. The following sub-sections describe the details of the modelling system, urban canopy scheme and the use of urban land categories for the West Midlands.

2.3.1 Configuration of the Weather Research and Forecasting (WRF) model

WRF was set up to include four nested domains, the largest covering Europe and part of the north Atlantic and the smallest covering the West Midlands and centred over Birmingham over a 78 x 81 km area (Figure 4).The domains had grid resolutions of 36 km x 36 km , 12 km x 12 km, 3 km x 3 km and 1 km x 1 km from the largest to the smallest domain, with feedback of variables from smaller grids to parent grids enabled. The terrain height for Domain 4 (the smallest domain) is shown in Figure 5. The meteorology for initial and lateral boundary conditions was provided by the ECMWF ERA-interim reanalysis data (Dee *et al*., 2011) at a spatial resolution of 1.5 degrees every 6 hours. There were 37 pressure levels above the surface to 1 hPa. There were 10 vertical layers configured below 1000 m, and BEP had 13 levels at a constant thickness of 5m. Land surface data used as an input to WRF for all domains were based on United States Geological Survey (USGS) 24 category land use data, and for the smallest domain (Domain 4) we used two local datasets to generate the urban categories (see below). We used the Noah Land Surface Model, a relatively complex community model, which is often coupled with an urban canopy scheme, and has 4 layers of soil moisture and temperature (Tewari *et* al., 2004). The longwave radiation scheme was the Rapid Radiative Transfer Model (RRTM; Mlawer *et al*., 1997) and shortwave was the Dhudia scheme (Dudhia, 1989). The boundary layer physics scheme was Bougeault-Lacarrere (Bougeault and Lacarrere, 1989), designed for use with the BEP urban scheme (Skamarock, 2008). The model time step was 180, 60, 20 and 5 seconds for the four domains, respectively, with output at every hour. Initial soil moisture was approximately 0.3 m^3 m^{-3} for the 4 layers.

2.3.2 The Building Energy Parameterization (BEP) scheme and land use classification

For urban land use types we used the BEP multilayer surface urban canyon scheme (Martilli *et al*., 2002) which accommodates 3 urban land use categories classed as a) Industrial/Commercial, b) High Intensity Residential or c) Low Intensity Residential. Within each of these urban classifications, thermal properties and urban morphology are defined to represent typical features of urban surfaces. The BEP scheme simulates the effects of the vertical distribution of heat, momentum and turbulent kinetic energy throughout the urban canopy layer, separated into a number of layers down to the surface (Martilli *et al*., 2002). Momentum and heat transfer processes through roads, walls and roofs, and radiation processes related to shadows and reflections are considered in the BEP scheme. Table 1 summarises some key parameters used for each of the urban categories; we used the default BEP parameters. Physical parameters such as height and width of roof, walls and roads varied between the 3 urban categories. In this study, the anthropogenic heat sources were from those implicitly included through heating from roofs, walls and the ground (90, 50, and 20 Wm^{-2} respectively).

For the West Midlands Metropolitan Area (which includes the cities of Birmingham, Wolverhampton and Coventry and has a population of around 2.7 million) the data used for urban classification was adapted from Owen *et al*. (2006), who originally classified the area into 8 separate urban land cover categories. These 8 categories were then aggregated to the required 3 urban categories for use with BEP, in conjunction with analysis of high resolution satellite images. For details on the West Midlands urban classification, see Owen *et al.* (2006). For the rest of the domain, (within the modelled Domain 4 but outside the West Midlands Metropolitan Area), the 3 urban land use categories were adapted from the Corine Land Cover 2000 data (available from the European Environment Agency http://www.eea.europa.eu/). The 3 urban surface classes adapted from Owen (2006) and the Corine Land Cover data were combined to create an urban land use dataset with 1 km x 1 km resolution (Figure 6) that was applied across Domain 4 only (corresponding to 40% of the total domain area), and the land use categories for 'non-urban' cells were taken from the USGS data, which is the default land-use dataset for WRF.

2.4 Model evaluation against observations during the heatwave period

In order to evaluate the performance of the model, we compared modelled output from WRF with observations taken from MIDAS Met Office sites within Domain 4. We used hourly data for the period under investigation from the four stations within Domain 4: WH and CV (Urban), EB (semi-urban/urban) and CH (rural). Because the grid cells in Domain 4 of the simulation are 1 km^2, linear interpolation from the temperatures given at the four corresponding nearest points was applied to represent values at the position of the observation station in each case, inverse weighted by distance to grid points. The hourly observed temperature fields measured at screen height were compared with the 2 m temperature field output by WRF. Figure 7 shows time series of modelled and observed hourly temperature for the four monitoring sites from the 2nd to 10th August 2003 (the first 24 hours of 1st August were used as spin-up) and Figure 8 shows these data presented using scatter plots. Correlation coefficients between modelled and observed temperatures are 0.94 for EB and CH and 0.93 for WH and CV. Figures 7-8 and the correlation coefficients illustrate that WRF is capturing the diurnal cycle in temperature well, although some of the maximum temperatures are not always reached by the model, particularly for CH, which could be attributed to the soil moisture being initialised too high during the heatwave period, and this is more apparent at this rural site. Of all the sites, temperatures simulated for EB are closest to observations. Table 2 summarises key statistics for each of the 4 station locations.

The use of WRF to simulate 2 m air temperature across the West Midlands provides a visual representation of the spatial extent of the UHI during a heatwave. Figure 9 shows simulated 2 m temperature for Domain 4, at 11pm on the 5th August, when the south-easterly wind was 3 m s^{-1} and the UHI was particularly enhanced. The locations of all the weather stations used in the analysis, and the location of central Birmingham (BC) are marked. The temperature ranges from around 16^{o}C in some rural areas to 23^{o}C in the central, urbanised area of Birmingham. Note the temperature at the location of EB weather station is 1 or 2 degrees lower than the hottest part of the domain, reflecting the semi-urban nature of the site. Overall, urbanised areas have higher temperatures than rural areas, and the main high temperature areas are not confined to Birmingham. Wolverhampton, Coventry and other urban areas also experience significantly higher temperatures than rural areas. There is some indication of the effects of horizontal wind advection in Figure 9, and this is investigated further in Section 3.2.

2.5 Comparison of urban and suburban temperature

The location of BC is in the middle of Birmingham central business district (latitude 52.5^{o}N, longitude -1.9^{o}W). In comparison with modelled temperatures coincident with EB weather station, we find that over the period 2nd-10th August 2003, BC was on average 0.35^{o}C warmer than EB. However, when considering the daily maximum and night-time minimum temperatures, the mean differences were 0.73^{o}C and 0.09^{o}C respectively, indicating that during the heatwave period, EB is slightly cooler than BC, but more importantly this effect is more marked in the daytime and less significant at night time. In fact, the maximum difference between BC and EB is around 2^{o}C during early afternoon on the 3rd August. This means that although using EB as an urban site means we capture night-time UHI effects, peak daytime temperatures are not representative of the daily maximum temperature in the city centre. This highlights the fact that by using EB observing station to represent Birmingham temperature, we are likely to be underestimating peak temperatures in the city centre by a number of degrees during heatwave conditions.

3 Results

3.1 Sensitivity test based on urban and rural land use simulations

To test the effects of urban land surfaces on local temperature, we ran a second WRF simulation ('rural') where we replaced all 3 urban land categories in Domain 4 (around 40% of the total area) with the USGS category corresponding to 'Dryland Cropland and Pasture', which is common in rural England. The original model run ('urban') can now be compared with the rural run to quantify the effects of urban surfaces on 2 m temperature as a sensitivity test. This can give an idea of the magnitude and spatial pattern of near surface temperature related to urban surface as compared with existing rural surfaces, which may have applications for urban planning exercises. The 2D temperature difference field between these two model runs ("urban-minus-rural") for any given time is denoted by $\Delta T_{u-r}(t,x,y)$, (where $\Delta T_{u-r} = T_u(t,x,y,z) - T_r(t,x,y,z)$, and in this case z = 2m). Figure 10 shows $\Delta T_{u-r}(t,x,y)$ for the same time as Figure 9. The most urbanised parts of Domain 4 – towards the centre of the domain – have the highest temperature differences and hence more urbanised areas have the largest temperature difference, as expected. A comparison of Figure 10 with Figure 6 shows that rural areas downwind of the south-easterly wind (to the northwest of the urban centre) also experience enhanced temperatures.

Figure 11 shows a time series of 2 m temperature in Birmingham city centre (BC) for urban and rural model simulations over the heatwave period. The rural run shows consistently lower temperatures than the urban run: on average the temperature difference is 3.2^{o}C, and reaches a maximum of 5.6^{o}C at 8am on the 3rd August. Table 3 lists mean and maximum temperatures for the urban and rural simulations as well as mean and maximum temperature differences for the heatwave period for a number of locations in the West Midlands Metropolitan area. Even the most rural location listed in Table 3 (CH) shows a mean urban-minus-rural temperature difference of 1.5^{o}C, which could reflect the fact that CH is still influenced by the nearby urban area of Birmingham, due to wind advection. The mean temperature difference ranges from 1.5^{o}C in CH (rural location) to 3.2^{o}C in BC (urban location) for the heatwave period. The maximum difference for each monitoring location is similar, ranging from 5.6^{o}C to 6.8^{o}C, and the largest maximum temperature difference is for Wolverhampton (Table 3). Although Wolverhampton is not as highly populated as Birmingham, the position of the monitoring station is very centrally located within the city, which may partially explain the large urban-rural temperature difference at this location. The 2 m temperature is sensitive to soil moisture, and therefore the results of the sensitivity experiment wil be influenced by soil moisture levels, particularly since CH has slightly lower validation statistics than the urban sites, which could be due to an overestimated soil moisture.

As part of the sensitivity analysis, we examined the influence of the urban surface on low level wind speed by comparing 10 m wind speeds at the centre of the domain (BC) between urban and rural model runs. This location is where the contrast between the wind speeds in each simulation is most pronounced since it is the most highly urbanised area. We found that the mean 10 m wind speed was 2 m s^{-1} lower in the urban run than the rural run at this location. The difference between the two runs was approximately the same for day and night time values, although mean wind speeds were lower in both runs during night time than day time (2.8 m s^{-1} and 3.3 m s^{-1} for the rural run and 0.8 m s^{-1} and 1.3 m s^{-1} for the urban run).

3.2 The influence of horizontal winds on the spatial pattern of the UHI

Although the UHI is usually most pronounced when wind speeds are low (Figure 3), it is likely that even low wind speeds can affect the spatial distribution of warm air associated with the conurbation area. For example, temperatures in rural areas downwind of a city may experience warmer conditions than those upstream, and Bohnenstengel *et al*. (2011) found that the rate of evolution of the UHI was different upwind and downwind of London.

In order to investigate the effect of horizontal advection associated with prevailing wind direction on the spatial distribution of the UHI, we propose a novel methodology by decomposing the UHI intensity into components relating to the time-mean intensity and those which are driven by the prevailing wind advection. For example, Figure 12 (left) shows a highly simplified one dimensional schematic of the temperature distribution that might be expected in an urban area and its surroundings for a sufficiently long period throughout which wind is assumed to be varying in both directions (left-to-right and right-to-left). The height of the 'urban' bar represents the relative temperature enhancement associated with local urban land surfaces, whereas the height of the 'rural' bars represents the relative temperature enhancement associated with wind advection. Panel a) represents a time mean temperature enhancement for the entire period. Panel b) is the temperature enhancement that we hypothesise for the case that the wind blows from a specified direction (in this case from left to right) for some proportion of the period illustrated in Panel a). Finally, to illustrate the 'advective' temperature enhancement associated with this specified wind direction, we remove the time mean field from the field whereby the wind direction is specified (Panel b minus Panel a). The result is the temperature enhancement that can be attributed to the influence of a particular wind direction, shown as a difference in temperature; areas upwind of the urban centre become negative and those downwind become positive (Panel c). An obvious advantage of this method is that the temperature enhancement associated with local urban land surfaces is removed. We now extend this methodology to two dimensions and classify mean 10 m wind fields into 4 different directional quadrants, based on the average 10 m U and V output for each hour, across Domain 4. The methodology to investigate the effect of horizontal advection on the 2 m temperature field is described in detail below, and an example for the case when wind is blowing from the north west is shown on the right hand side of Figure 12.

1) We first sorted each hourly time step of the original 'urban' model run during the heatwave period by 10 m wind direction, i.e., winds from the north west (NW), south west (SW), north east (NE) and south east (SE), each of which includes all directions from a range of 90° in the respective quadrant. During the period from the 2nd to the 10th August 2003, the 10 m wind direction was from the SE for approximately 48% of the time (104 hours), from the SW and NW 18% of the time (40 hours) and from the NE for 15% of the time (32 hours).
2) For any given hour t and height z (z = 2 m in this instance), we define a 'rural temperature', T_{rural}, as the mean temperature along the 2 inlet sides of Domain 4. For example, for the south easterly wind quadrant, the rural temperature is the mean temperature along the south and east edges of Domain 4. So that, for any given z and t, we define $\Delta T(x, y) = T(x, y) - T_{rural}$, which represents the enhancement of temperature due to the processes inside Domain 4, including urban surface heat transfer. With an assumption that urban surface heat transfer dominates over other processes, $\Delta T(x, y)$ represents the UHI intensity. In addition, we defined a 'time-mean UHI intensity field' as the long-term mean of $\Delta T(x, y)$, and assumed that the 2003 heatwave period (a total of 216 hours) is sufficiently long to represent a time mean field. This field is denoted by $\overline{\Delta T}(x, y)$. It is noted that the enhancement of temperature can be hypothetically decomposed into two separate fields, the first one purely determined by the local characteristics (e.g. local land-use composition), denoted by $\overline{\Delta T}_{loc}$, and the second one purely determined by wind advection, denoted by $\overline{\Delta T}_{adv}^{tm}$ (where the superscript of 'tm' represents the 'time-mean', i.e. all wind directions during the averaging period, and Δ denotes an incremental temperature related to land surface type). Namely,

$$\overline{\Delta T} = \overline{\Delta T}_{loc} + \overline{\Delta T}_{adv}^{tm}. \qquad (1)$$

We call the quantity, $\overline{\Delta T}_{adv}^{tm}$, the "time-mean UHI by advection" (see Box 1). The effect of wind advection on the time-mean UHI field, $\overline{\Delta T}_{adv}^{tm}$, is a 'spread' of UHI away from the urban centre in all directions, which can be seen in the right panel of Figure 12a.

3) For each wind direction regime we then obtained the mean spatial (2D) temperature enhancement, denoted by $\overline{\Delta T}^{(i)}(x, y)$, where i = 1,2,3,4 is the index for the four wind directions. We subtracted the 'time-mean temperature' component from $\overline{\Delta T}^{(i)}(x, y)$ for all four wind direction regimes to obtain a new 2D temperature field, $\overline{\Delta T}^{(i)} - \overline{\Delta T}$, following the methodology illustrated in Figure 12.
4) We finally subtract a constant which is the mean temperature along the 2 inlet sides of domain 4 for each wind direction panel. This corrects for the small bias in temperature which exists between winds originating from different directions, so that the panels are comparable. However, effects due to the larger-scale (e.g. from Domain 3) warm/cold advection into Domain 4, such as fronts, are not accounted for in the current methodology.

We claim that this new 2D UHI field denoted by $\overline{\Delta T'}_{adv}^{(i)}$ contains only the non-local, advection-induced UHI based on the arguments described in Box 1.

Box 1. The additional advection-induced UHI.

i. We can decompose the UHI intensity *at any given hour* into three terms:

$$\Delta T = \Delta T_{loc} + \Delta T_{adv} = \Delta T_{loc} + \overline{\Delta T}_{adv}^{tm} + \Delta T'_{adv} \qquad (2)$$

where ΔT_{loc} is the UHI intensity purely determined by local characteristics rather than being influenced by winds, ΔT_{adv} is the UHI due to wind advection, which can be further decomposed into the time-mean UHI by advection, $\overline{\Delta T}_{adv}^{tm}$, and the additional advection term for this hour above the time-mean UHI by advection, $\Delta T'_{adv}$. It is noted that both ΔT_{loc} and $\overline{\Delta T}_{adv}^{tm}$ are independent of wind direction and thus the decomposition (2) defines $\Delta T'_{adv}$ which is wind-direction dependent.

ii. For all hours that fall into the i-th wind direction quadrant (i=1,2,3,4), averaging (2) yields

$$\overline{\Delta T}^{(i)} = \overline{\Delta T}_{loc}^{(i)} + \overline{\Delta T}_{adv}^{(i)} = \overline{\Delta T}_{loc} + \overline{\Delta T}_{adv}^{tm} + \overline{\Delta T'}_{adv}^{(i)} \qquad (3)$$

Where the notation $\bar{\varphi}^{(i)}$ represents an average operator over the i-th wind direction quadrant for variable φ; thus $\overline{\Delta T'}_{adv}^{(i)}$ is the averaged additional advection UHI intensity on top of $\overline{\Delta T}_{adv}^{tm}$ for this wind direction quadrant, and $\overline{\Delta T}_{loc}^{(i)}$ is independent of wind direction (equal to $\overline{\Delta T}_{loc}$). This assumption is reasonable if statistical distributions of meteorological quantities are independent of wind direction.

iii. An average of (2) over all hours of the period gives the time-mean UHI intensity field, Equation (1).

iv. Therefore, subtraction of (1) from (3) yields:

$$\overline{\Delta T}^{(i)} - \overline{\Delta T} = \overline{\Delta T'}_{adv}^{(i)} \qquad (4)$$

which does not contain the UHI intensity purely determined by local characteristics ($\overline{\Delta T}_{loc}$), nor the time-mean UHI intensity by advection ($\overline{\Delta T}_{adv}^{tm}$). We interpret $\overline{\Delta T}^{(i)} - \overline{\Delta T}$ as the "additional UHI component by advection" above the time-mean UHI by advection.

In theory, the number of wind sectors which may be chosen for classification is not limited to 4. It should be noted that for the special case whereby the wind blew continuously from the same direction for the duration of the period, Panels a) and b) of Figure 12 would be identical, and the resulting distribution in Panel c) would be zero. We accept this limitation due to the fact that this is a highly idealised condition that would rarely be realised, especially over longer time periods. For the heatwave period in 2003, the wind direction varied between all 4 wind direction quadrants. The calculated fields of $\overline{\Delta T}'^{(i)}_{adv}$ for 'night-time' hours (i.e. 8 pm to 7 am inclusive) are presented in Figure 13. During these hours, the wind was from the NW for 23 hours, from the NE for 27 hours, from the SW for 10 hours and from the SE for 49 hours. As the figure shows, by using this method, the 'local' UHI pattern closely associated with the local urban land-use (clear in Figure 10) is no longer visible; this is evident from equation (4) because $\overline{\Delta T}_{loc}$ no longer appears in the 2D UHI fields. Furthermore, we know that the time-mean UHI by advection ($\overline{\Delta T}^{tm}_{adv}$) also does not appear in the fields; if $\overline{\Delta T}^{tm}_{adv}$ were there, we would see 'diffusive-like' patterns attached to the urban areas. A limitation of this method is that the hypothetical terms of $\overline{\Delta T}_{loc}$ and $\overline{\Delta T}^{tm}_{adv}$ cannot be separated from the model output of $\overline{\Delta T}(x, y)$ in (1); similarly, ΔT_{loc} and ΔT_{adv} cannot be separated in (2), and $\overline{\Delta T}^{(i)}_{loc}$ and $\overline{\Delta T}^{(i)}_{adv}$ cannot be separated in (3).

As shown in Figure 13, there are clear differences in $\overline{\Delta T}'^{(i)}_{adv}$ between regions which are upwind and downwind of the urban centre in Domain 4, particularly for SE and SW wind directions, where temperature differences can be up to 2.5°C (Figure 13). This may be partially explained by the geographical orientation of the conurbation area. Figure 6 shows that the urban land-use spatial pattern in Domain 4 tends to be aligned along the SW-NE direction. It is also shown in Figure 13 that the regions of high temperatures appear discrete and appear to be closely related to the land use pattern, as might be expected as a reflection of the heat emitted from urban materials. The intensity of the advective UHI component is enhanced by accumulated heat collected by an air parcel travelling along its path.

Figure 13 also shows that the advective UHI pattern for the NE wind direction appears to be inconsistent with the other directions (seemingly an advective pattern for NW wind). A careful examination shows that this is mainly attributed to two transient periods (7th and 10th August) during which wind direction changed from NW to NE within a few hours and the advected warm air by the NW wind in the previous hours dominates the temperature field. Because the time scale of advection is L_{domain}/V, where L_{domain}~80,000 m is the domain size and V~2 m s^{-1} is wind speed, the influence of the inlet wind direction on the flow in the entire interior domain may last up to 10 hours.

Furthermore, we examined the three-dimensionality of the UHI by investigating the 2D temperature field at 4 levels, from the ground up to around 70 m and found that UHI intensity falls off with height such that at higher levels above ground, the UHI becomes less prominent (Figure 14). In this case, the inlet temperature along the upwind sides of the domain has been subtracted for each wind direction, but the time-mean temperature has not been subtracted. At ground levels, the UHI is visible in the centre of the domain, but at the 4th level, it is no longer clearly characterised. At this level, however, the temperature distributions induced by the larger-scale cold/warm advection from Domain 3 are still visible.

4. Conclusions

By using a mesoscale regional meteorological model with an urban canopy scheme in combination with detailed local urban land-use data, we have simulated air temperatures in Birmingham and the West Midlands Metropolitan region during the August 2003 European heatwave at a high spatial resolution. We validated the model against observations from four weather stations to test for satisfactory performance. The motivation was to investigate the effect of urban surfaces on air temperatures during a heatwave period, where excess heat poses a risk to health. This will allow more accurate estimates of health burdens to be made, when considering future climate scenarios, and reduce the risk of underestimation of health impacts due to heat in future. The novel methodology relating to horizontal advection has the potential for improvements to or parameterizations for diagnostic models which do not explicitly include dynamics and where local conditions are driven largely by surface land use type.

The spatial analysis of the extent of the UHI across the region showed that the presence of urban surfaces in the West Midlands led to an enhancement of local temperatures. For Birmingham City Centre, the difference in temperature between the urban and rural simulations during the heatwave period was on average 3.2^{o}C but reached a maximum of 5.6^{o}C, and Wolverhampton had a maximum temperature difference of 6.8^{o}C. The rural site of Coleshill was found to experience temperatures 1.5^{o}C higher than expected, suggesting that even though it is outside of the main urban area, it is still influenced by the urban heat island effect.

Finally, a novel generic methodology enabled the examination of the extent of horizontal advection of warm air downwind of the conurbation area. By using this method it was possible to quantify how much temperatures in rural areas can be enhanced by the presence of nearby cities. We found that temperatures downwind of cities were up to 2.5^{o}C warmer than they were upwind. This non-local nature of the UHI is a further justification for the use of mesoscale meteorological models to quantify the potential influence that urban surfaces have both within cities and downwind of city centres. There are limitations in the methodology, which is largely a two-dimensional analysis; however there is the potential for useful application to communities which carry out health impact or environmental assessments, which use surface level data for highly populated areas.

The analysis indicates that the large urban populations residing in, or close to, cities in the West Midlands are likely to be exposed to higher temperatures during heatwaves than populations residing further outside urbanised areas. Since climate change temperature projections such as those provided by the UKCP09 do not resolve urban features, it is likely that the full extent of the health impacts related to heat are not accounted for in studies based solely on climate projections. Therefore, mesoscale meteorological modelling can be a valuable tool for assessing the health impacts of hot weather in urban areas. The modelling methodology presented here has the potential for application to other cities to quantify UHI intensity and estimate potential health burdens associated with heatwaves. In addition, the novel approach for investigating the effects of horizontal advection may be applied to other models with limited dynamics, by inclusion of land use information and some external wind information.

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Table 1. Physical parameters used by the BEP scheme for all 3 urban categories.

Parameter	**Roof**	**Walls**	**Ground/Road**
Albedo (fraction)	0.20	0.20	0.15
Surface emissivity	0.90	0.90	0.95
Thermal conductivity ($J\ m^{-1}\ s^{-1}\ K^{-1}$)	0.6950	0.6950	0.4004
Heat capacity ($J\ m^{-3}\ K^{-1}$)	$1.32x10^6$	$1.32x10^6$	$1.40x10^6$

Table 2. Mean temperature, standard deviation, root mean squared deviation and correlation coefficients for observed and modelled temperatures at 4 locations.

	Edgbaston		Wolverhampton		Coventry		Coleshill	
	Obs	Mod	Obs	Mod	Obs	Mod	Obs	Mod
Mean (°C)	21.65	21.46	21.53	21.37	21.73	21.20	21.08	20.60
Standard deviation (°C)	4.86	4.88	5.26	5.08	5.32	4.90	5.84	4.89
RMSD (°C)		1.66		1.89		1.94		2.14
Correlation		0.94		0.93		0.93		0.94

Table 3. Simulated values for urban and rural model runs for a number of locations for the period 2nd-10th August 2003 in °C. ΔT represents the difference between urban and rural runs.

Location	Mean urban T	Max urban T	Mean rural T	Max rural T	Mean ΔT	Max ΔT
Birmingham (BC)	21.8	31.7	18.6	28.9	3.2	5.6
Edgbaston (EB)	21.5	30.6	18.5	28.8	2.9	5.6
Coventry (CV)	21.2	30.6	18.9	29.1	2.3	6.0
Wolverhampton (WH)	21.4	31.3	18.3	28.2	3.1	6.8
Coleshill (CH)	20.6	31.2	19.1	29.0	1.5	5.6

Figure 1. Geographic area covered by the smallest domain in the WRF modelling set up, including Birmingham, Wolverhampton, Coventry, the West Midlands Metropolitan area and some of the West Midlands administrative region. Reproduced by permission of Ordnance Survey on behalf of Her Majesty's Stationery Office, © Crown Copyright and database right. 2014. All rights reserved. Ordnance Survey Licence number 100016969/100022432.

Figure 2. Observed air temperature at screen height for Coleshill (rural) and Edgbaston (semi-urban) Met Office MIDAS stations from 2nd to 10th August 2003.

Figure 3. Time series of observed hourly wind speed at Coleshill and UHI intensity throughout the heatwave period.

Figure 4. Nested configuration of WRF with 4 domains, centred over the West Midlands, UK.

Figure 5. Terrain height in metres across Domain 4. Locations labelled are WH-Wolverhampton, EB-Edgbaston, CH-Coleshill and CV-Coventry.

Figure 6. Urban land use categories across Domain 4. Locations of weather stations and the centre of Birmingham (BC) are indicated by black diamonds.

Figure 7. Time series of observed (solid) and modelled (dashed) hourly temperature at 4 sites in Domain 4.

Figure 8. Modelled (2m) versus observed (screen height) temperatures for four sites in Domain 4: a) Edgbaston, b) Wolverhampton, c) Coventry and d) Coleshill. The dashed line represents a reference at 1:1 and the solid grey lines represent the equations of the least squares fit.

Figure 9. WRF simulation of 2 m temperatures for Domain 4, for 2300 local time on the 5th August 2003. Station positions represented by asterisks: WH-Wolverhampton, EB-Edgbaston, BC-Birmingham City Centre, CH-Coleshill and CV-Coventry. The arrow indicates the mean wind direction for the hourly time step.

Figure 10. The difference in 2 m temperature between the urban and rural model simulations for Domain 4 at 2300 local time on August 5th 2003 in ^{o}C. Station positions are marked as in Figure 9.

Figure 11. Simulated temperature at 2m in Birmingham City Centre during 2nd-10th August 2003 for the urban run (black, dashed) and rural run (green, solid line).

Figure 12. A simplified, one dimensional schematic (left) to illustrate a) the mean temperature distribution averaged over a specified time period in urban and rural areas ($\overline{T}$); b) the hypothesised temperature distribution when a positive wind vector is applied (T_+); and c) the 'advective' wind component, $T_{adv} = T_+ - \overline{T}$ whereby the time mean temperature field is removed from the field whereby the wind is blowing from a specified direction. The panels on the right illustrate an example extended to 2 dimensions, where wind originates from the north west. Colour scale is 2 m temperature (^{o}C), with north west inlet temperature (mean temperature along north and west sides) removed.

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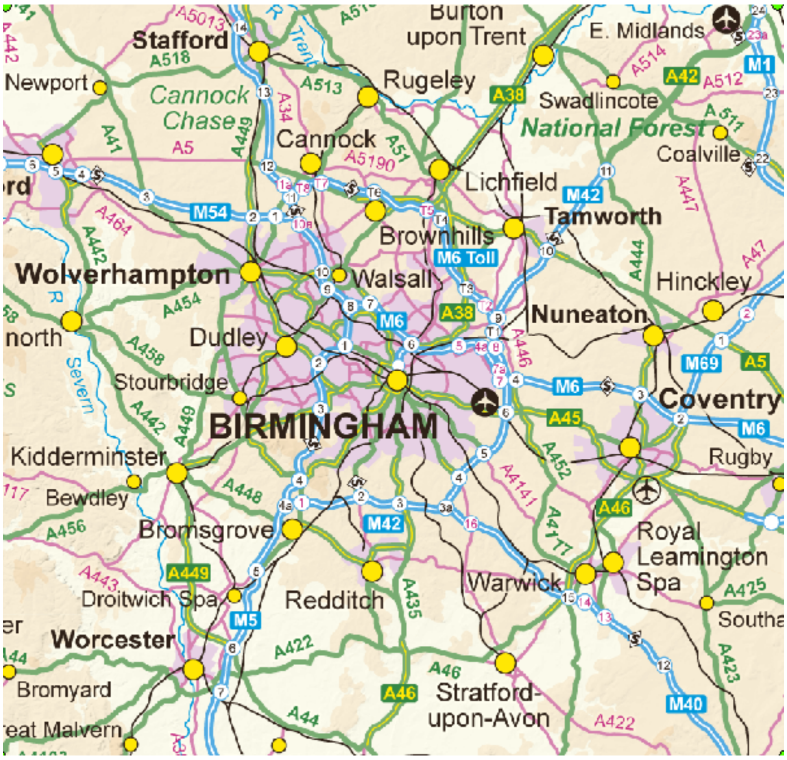

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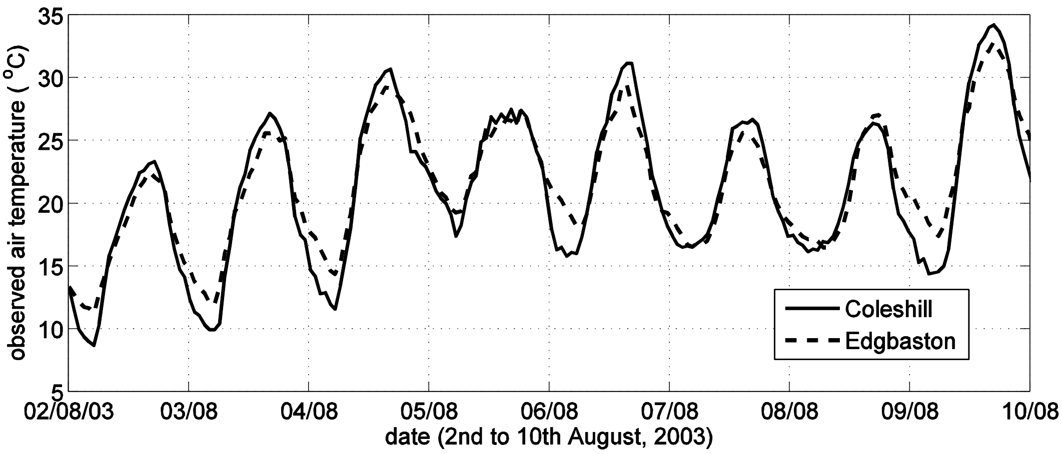

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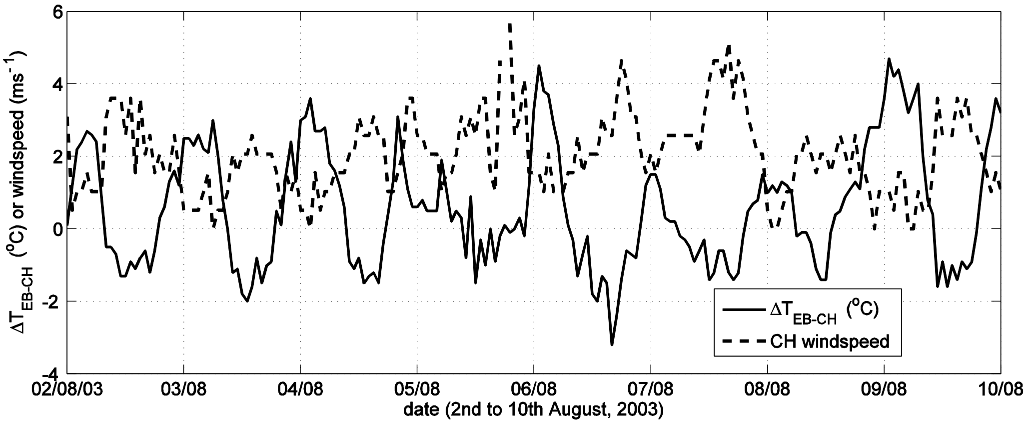

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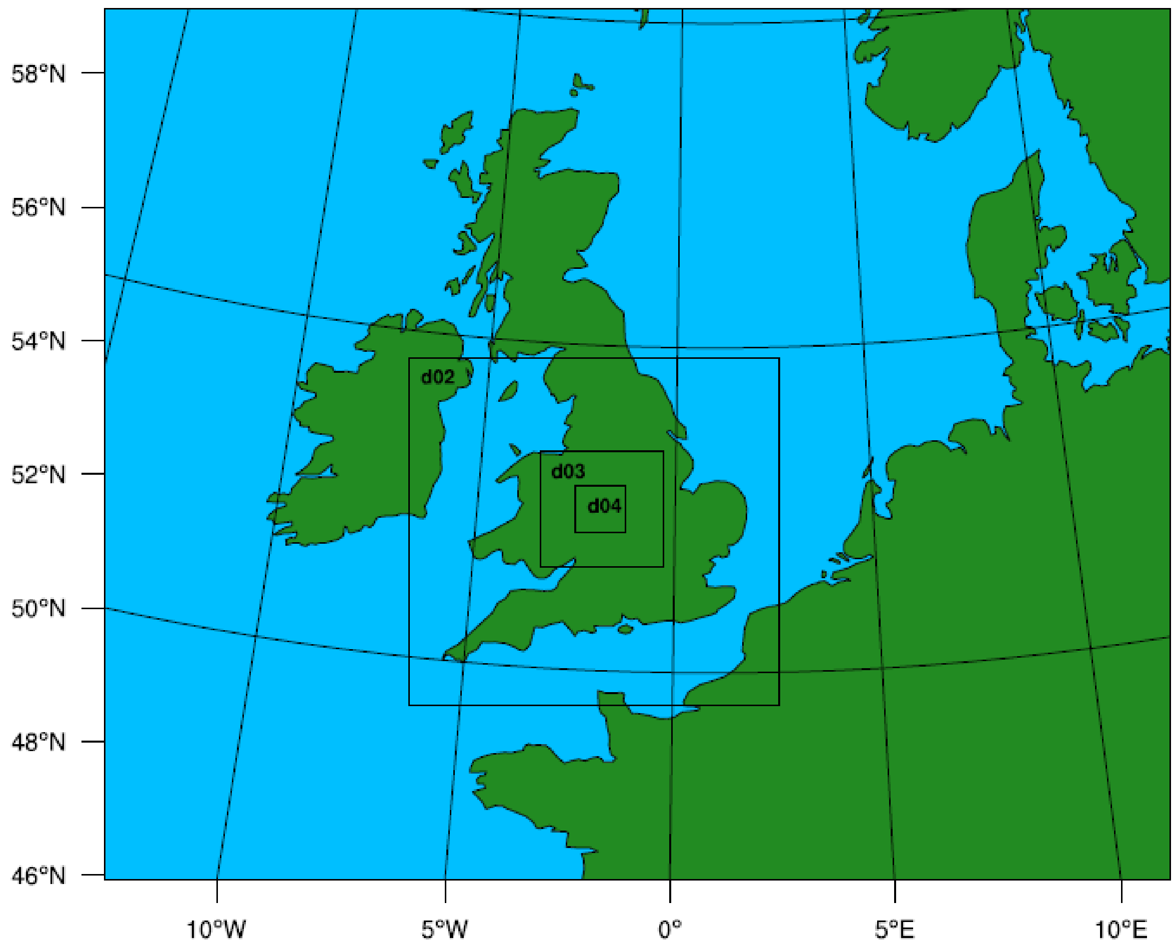

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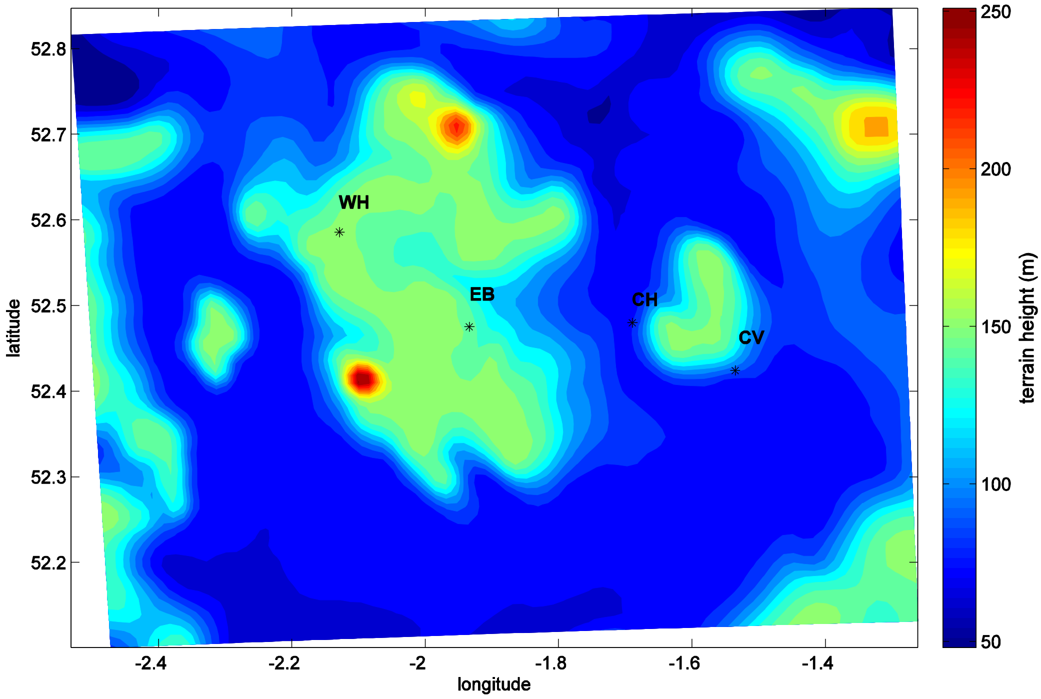

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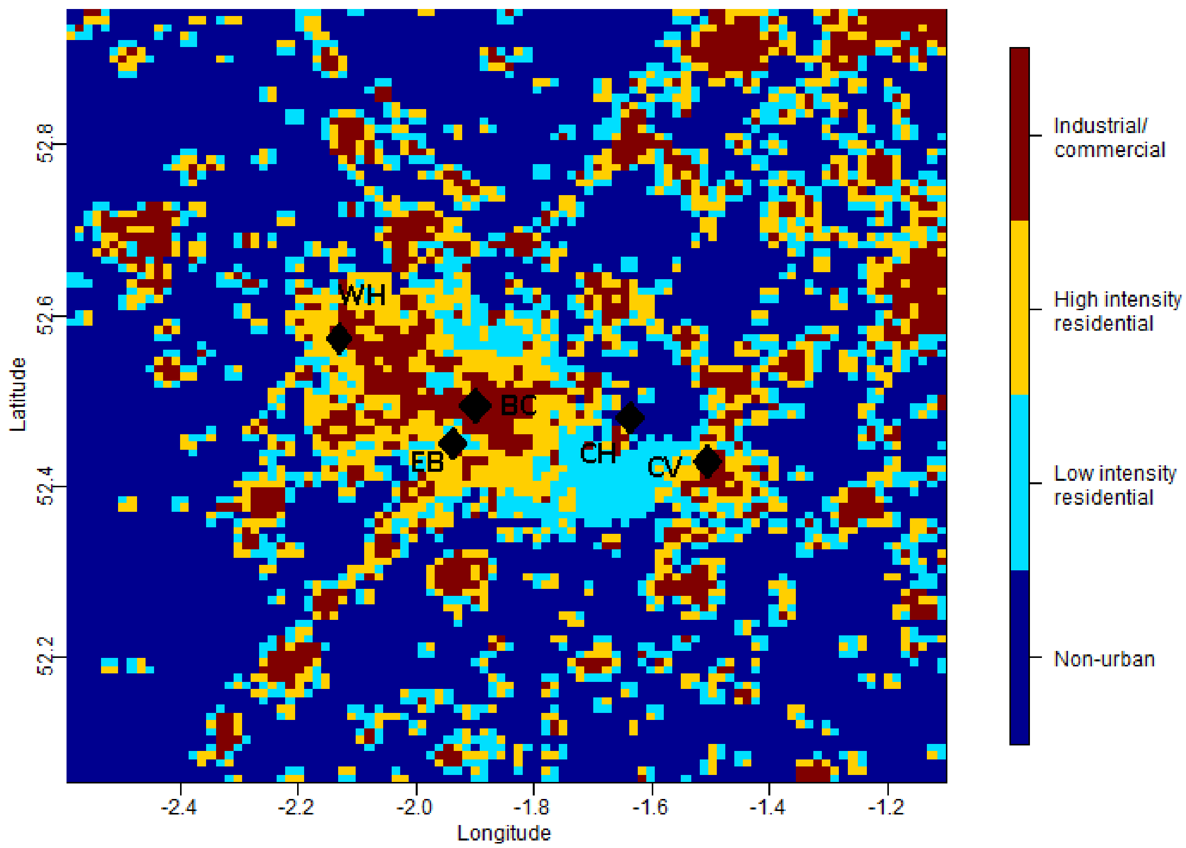

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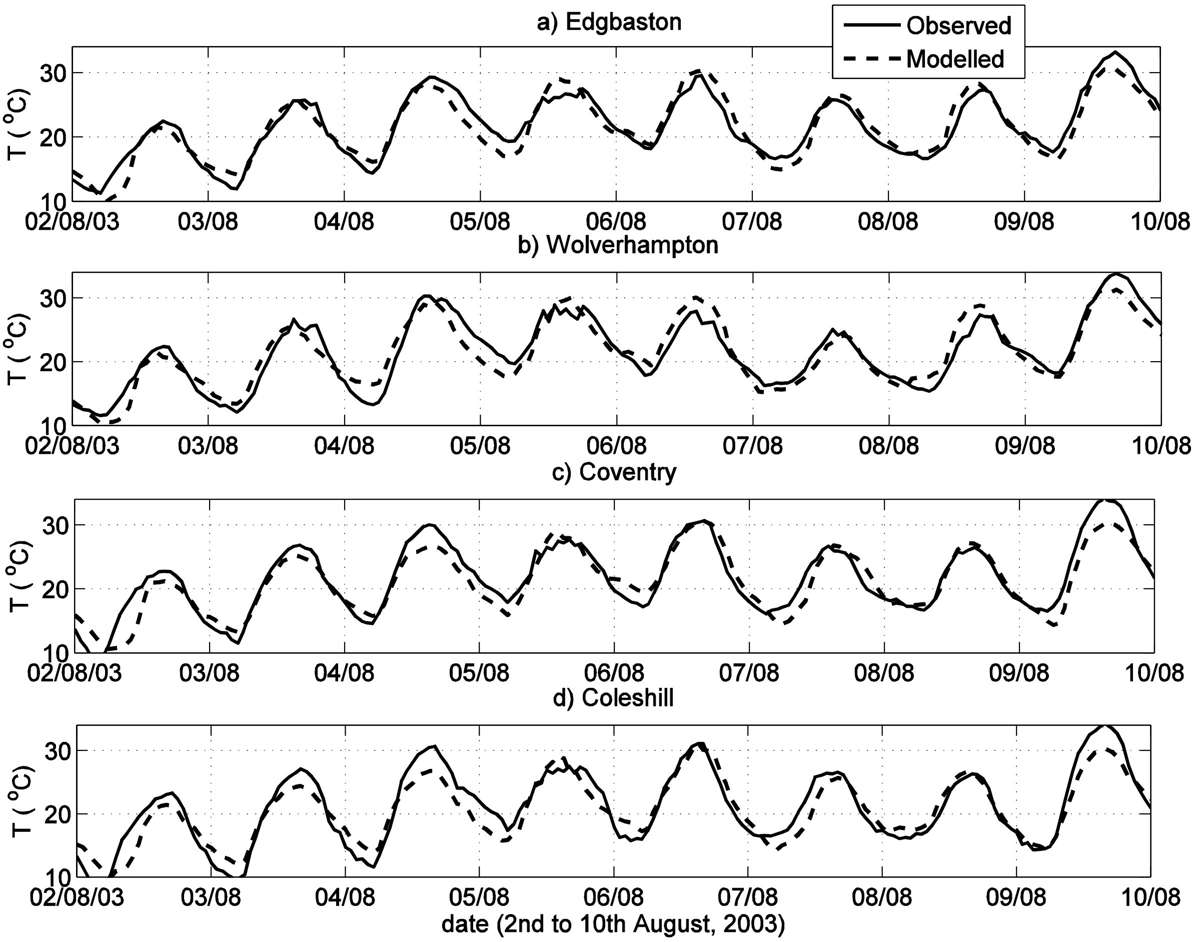

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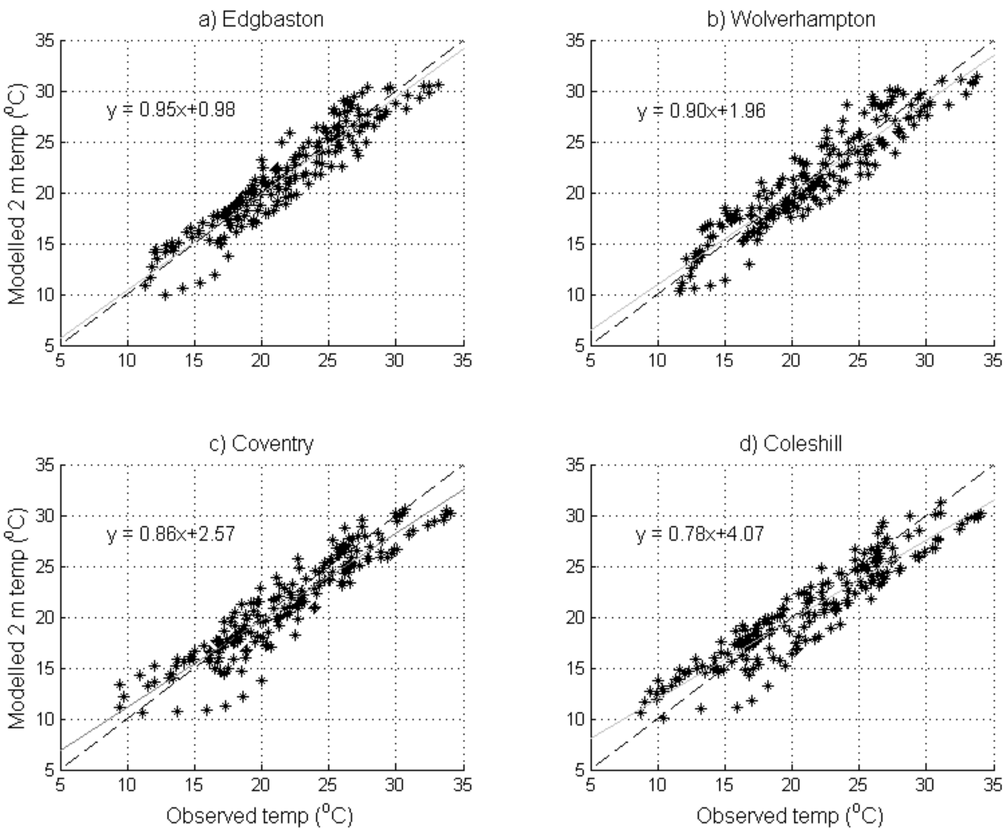

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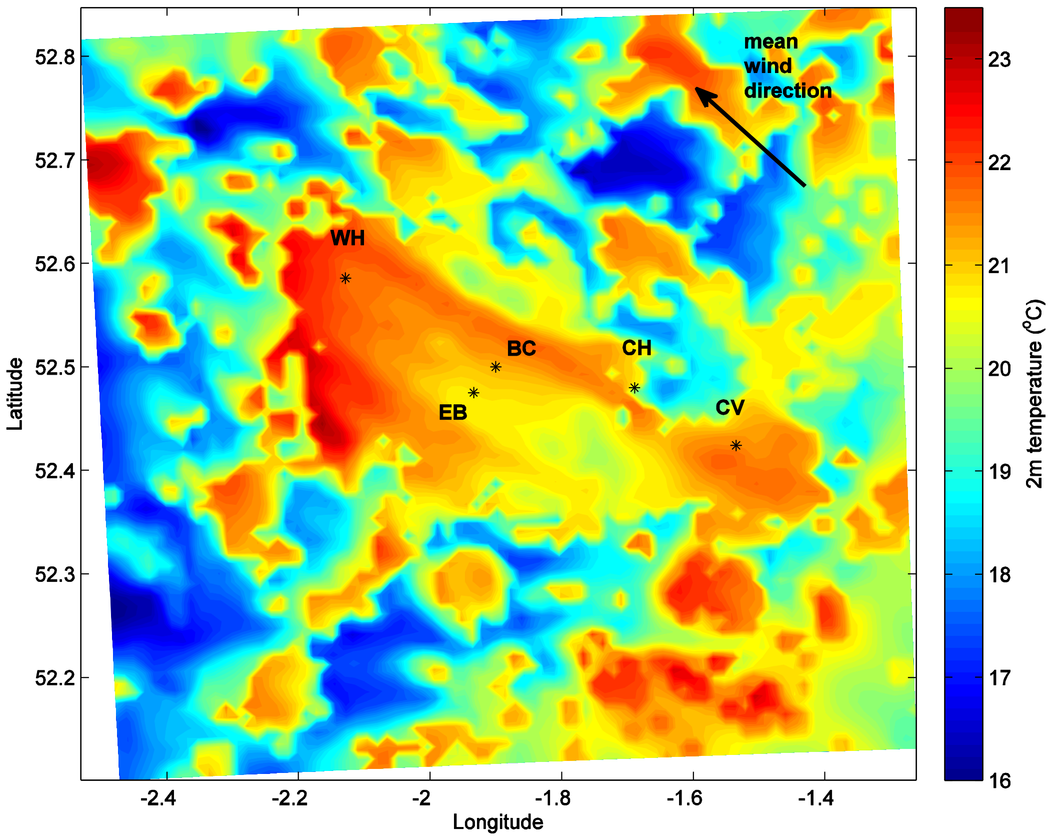

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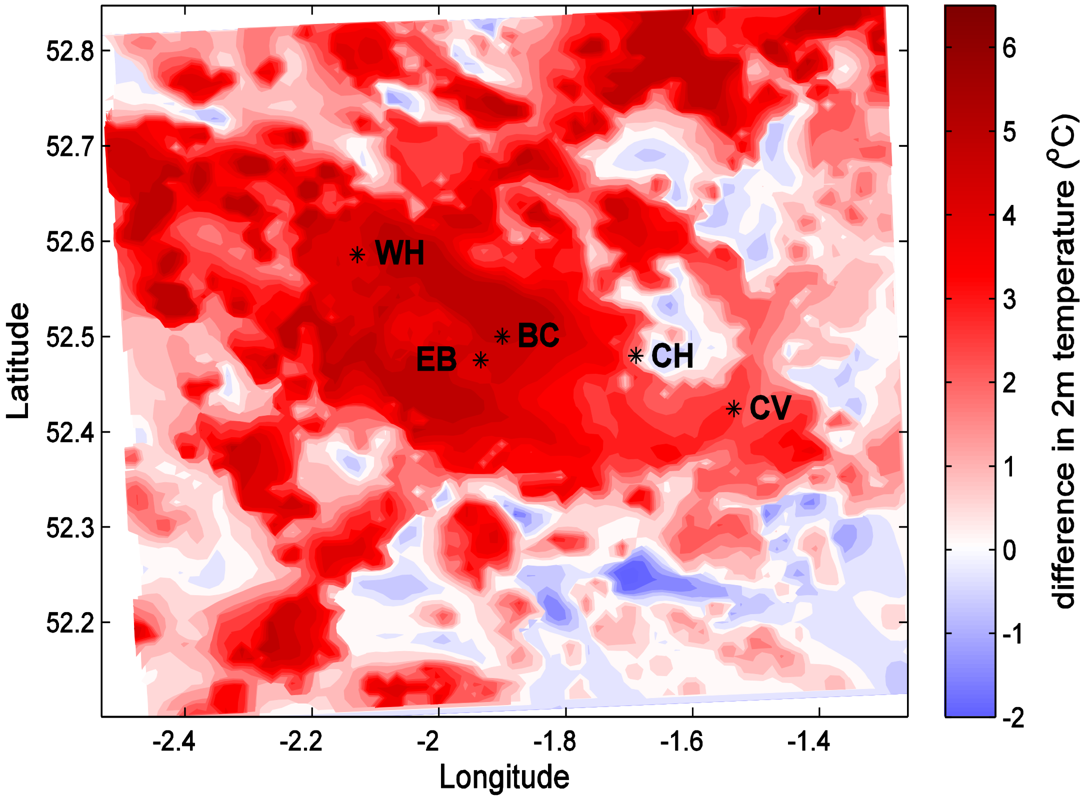

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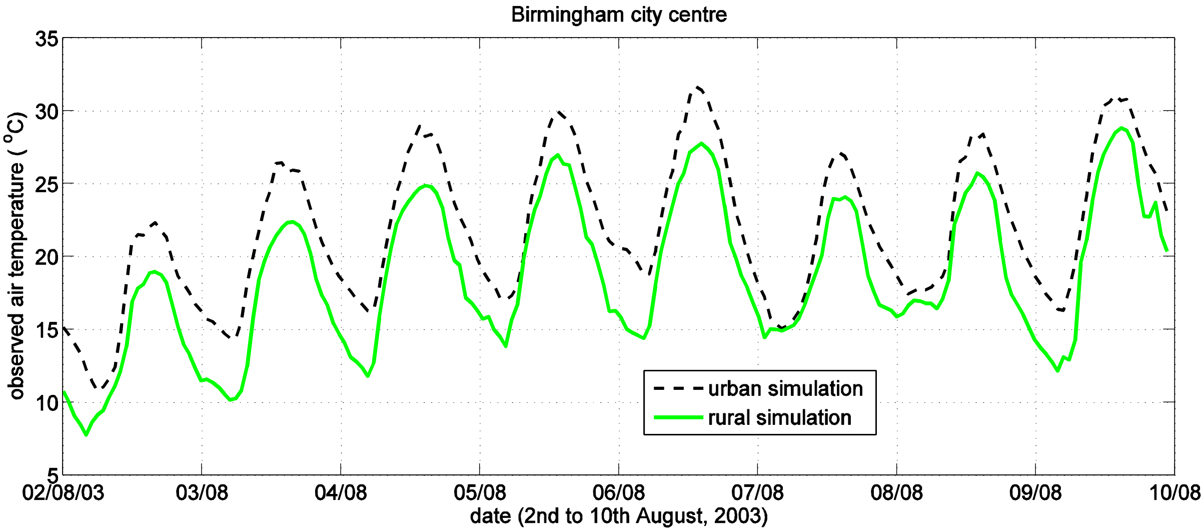

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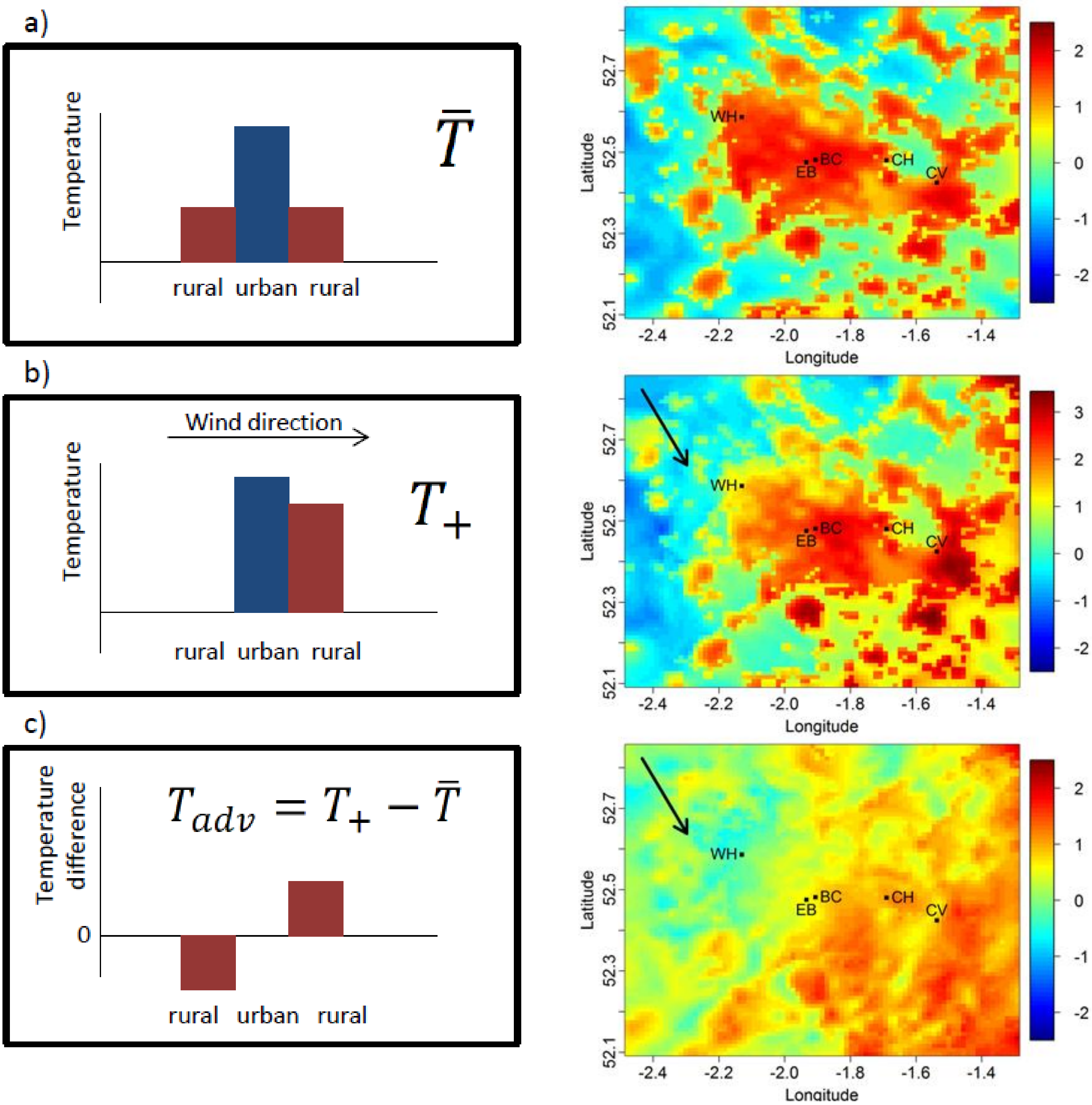

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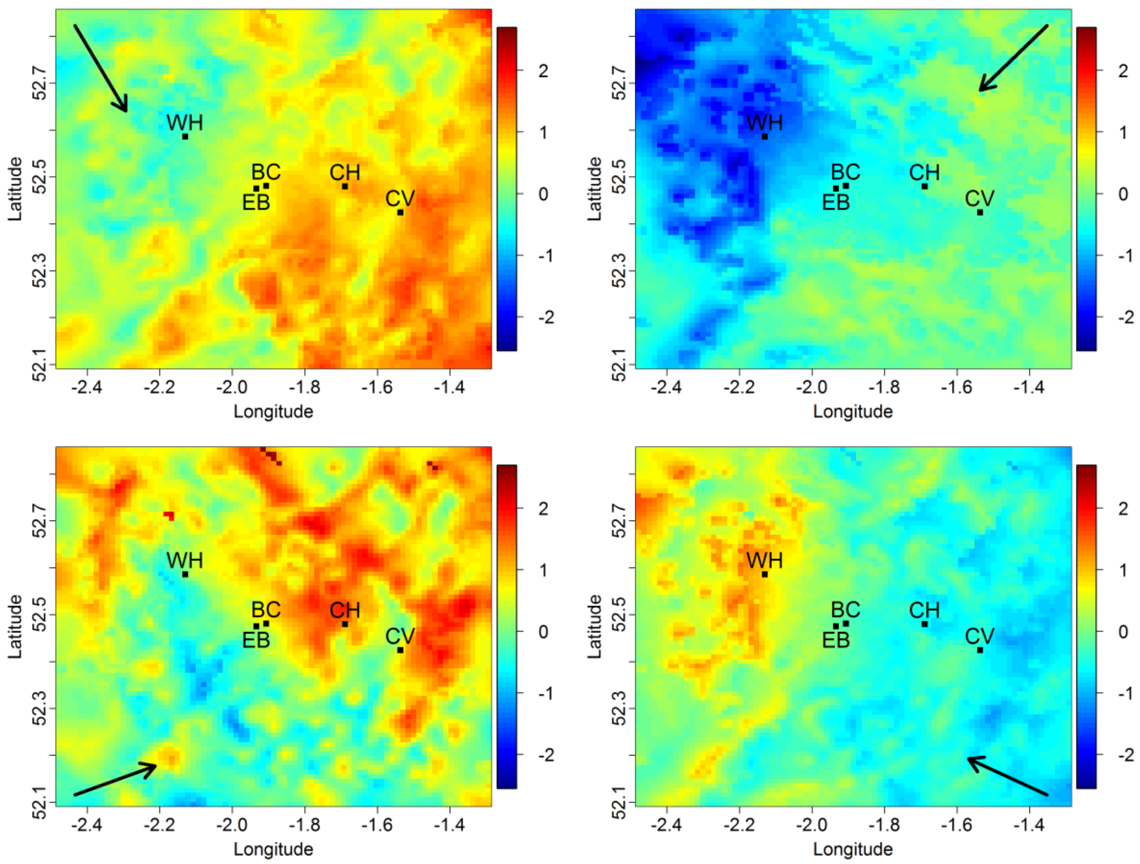

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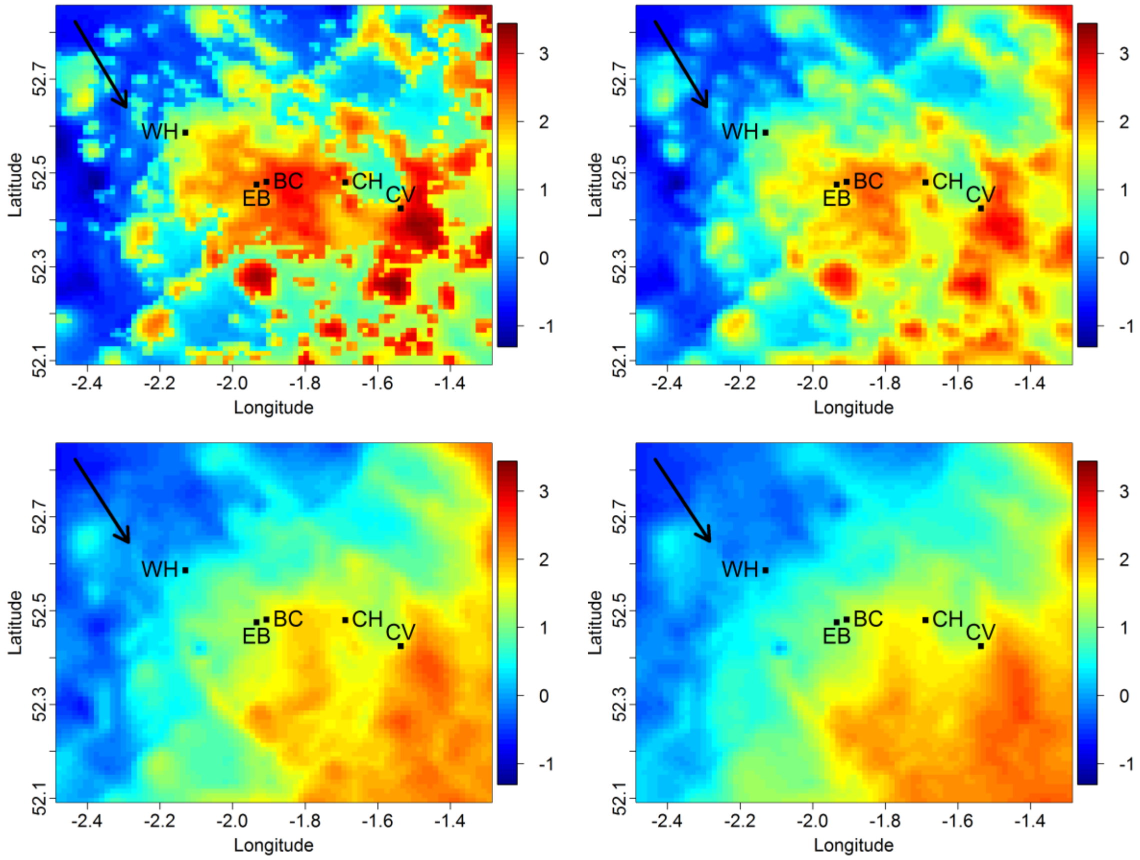

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